CHAPTER 2

WIND PROFILER THEORY AND TECHNOLOGY

2.1. **Theory.** Radar (RAdio Detection And Ranging) technology has undergone continuous refinement since its introduction early this century. “Radar is an addition to man's sensory equipment which genuinely affords new facilities.” So starts the Massachusetts Institute of Technology (MIT) Radiation Laboratory Series, a set of 27 textbooks published in 1947, which thoroughly describes the radar technology critical to the defeat of the Axis Powers in World War II. Theoretical studies in the 1950s indicated that radio waves are scattered by turbulence in the atmosphere in a predictable way that might allow monitoring of atmospheric parameters. Conventional weather radars detect reflections from objects in the air (e.g., hydrometeors), rather than the air itself. Wind profiling radars, on the other hand, depend on the scattering of electromagnetic energy by minor irregularities in the index of refraction, which is related to the speed at which electromagnetic energy propagates through the atmosphere. When an electromagnetic wave encounters a refractive index irregularity, a minute amount of energy is scattered in all directions. Backscattering, i.e., scattering of energy toward its point of origin, occurs preferentially from irregularities of a size on the order of one-half the wavelength of the incident wave. Because the refractive index fluctuations are carried by the wind, they can be used as tracers. Also, because these irregularities exist in a size range of a few centimeters to many meters, most wind profilers operate at frequencies well below those of conventional weather radars. Experiments in the 1960s verified the theory and showed that atmospheric structure from the surface up into the stratosphere could be detected and many atmospheric processes studied (e.g., Hardy and Katz 1969). In the mid-1970s the National Oceanic and Atmospheric Administration (NOAA) Aeronomy Laboratory began a research program that showed for the first time that tropospheric winds could be measured by very-high-frequency (VHF) (30–300 MHz) Doppler radar that used the Doppler frequency shift of signals scattered from atmospheric turbulence to monitor wind profiles from near the surface to well into the stratosphere (Ecklund et al. 1979).

The general principles of the wind profiler are detailed by, among others, Balsley and Gage (1980) and Rottger and Larsen (1990). Here we primarily address a specific type of radar wind profiler, the ultrahigh-frequency (UHF) (300–3000 MHz) Doppler system that is widely used in the United States. Other radar frequencies, primarily VHF but also microwave, are mentioned where applicable. A different method of wind measurement with numerous variations, called the spaced-antenna (SA) method, may also be used to derive wind profiles. The SA method has not been widely used in the United States, but Doviak et al. (1995) describe a 33-cm-wavelength SA system.

2.2. **Description of the Technology**. The UHF Doppler wind profiler produces vertical profiles of the horizontal and vertical wind by measuring the radial velocity of the scatterers as a function of range on three or five antenna beam positions (Fig. 2-1). The method of wind measurement is described in detail by Strauch et al. (1984); the following is a brief summary.

One antenna beam is pointed toward zenith, and the other two or four beams are pointed about 15 degrees off-zenith with orthogonal azimuths (three-beam systems) or orthogonal and opposite azimuths (five-beam systems). The beam-pointing sequence is typically repeated every 1–5 min. More than one range resolution mode may be used at each beam position. The Doppler velocity spectrum is computed for each radar resolution cell during a dwell period; more than 10^5 radar pulses are commonly used to measure each Doppler spectrum. Useful radial velocity estimates can be made with a per-pulse signal-to-noise ratio (SNR) below -40 dB. Signal processing involves (1) coherent integration of the complex video signal, (2) spectral analysis, (3) incoherent integration of Doppler spectra, (4) isolation of the signal spectrum from the signal-plus-noise spectrum, (5) velocity calculation, (6) temporal averaging of the radial velocities for a number of beam position sequences, and (7) the calculation of wind profiles. Nearly all UHF Doppler wind profilers operate like this, with very few changes in the basic technique during the past 15 years.

To measure wind profiles from velocity measurements made at three- or five-beam pointing positions, we assume that the wind field has local horizontal uniformity. Three unknowns (u,v,w) can be found from three radial velocities, or redundantly from a five-beam system. In some situations, such as the convective boundary layer (CBL) and convective precipitation, local horizontal uniformity cannot be assumed. When the wind field is not horizontally uniform over distances of the order of the separation of the radar resolution cells (a distance that increases with altitude and is on the order of 3 km at 10 km altitude), there are potentially two types of errors in the horizontal wind measurement: (1) the horizontal wind measured at the resolution cell is in error because of horizontal gradients of w, and (2) the horizontal wind above the profiler is not the same as that measured at the resolution cells because of gradients of u or v.

Although evaluation of the degree of local uniformity, i.e., horizontal homogeneity and stationarity, is possible using systems with more than three beams, currently implemented signal processing does not support these checks. Instead, it has traditionally been assumed either that uniform conditions exist or that time averaging (typically over 1 hour) will significantly reduce errors from these effects. Of course, neither assumption may be valid. Spatial variability of radial velocities across different antenna beams (e.g., due to gravity waves, convection, or precipitation) may generate meteorological noise in the wind component estimates. When high-time-resolution wind measurements are required, an assessment of the contribution of meteorological noise should be provided in the form of an error estimate based on separate evaluations of the temporal and spatial variability of the wind. Temporal variability on each antenna beam can be established from time series of measurements, whereas horizontal spatial variability across antenna beams requires four or more antenna beam-pointing directions.

Unfortunately, the radar signal is not always the result of scattering from refractive turbulence in the radar resolution cell. The UHF Doppler method described earlier in this section performs quite well for refractive index scattering (if the winds are locally horizontally uniform), but scattering from other targets can introduce serious errors in wind measurements. Scattering from hydrometeors (rain, snow, cloud droplets, ice crystals) can be much greater than that from refractive turbulence. This effect is more pronounced at higher frequencies. When this occurs, the profiler cannot measure the vertical wind; rather, it measures the mean fall speed of the hydrometeors. However, the profiler can still measure the mean horizontal wind if there is local horizontal uniformity of the wind and of the mean particle fall speed. Problems caused by other scatterers are discussed in section 2.4.

2.3. **Strengths and Potential**. The wind profiler can measure vertical profiles of horizontal and vertical wind in nearly all weather conditions with time resolution on the order of 10 min or longer and vertical range resolution as small as a few tens of meters. The resulting quasi-continuous time-height cross sections of the horizontal wind profiles provide interesting detail not seen with other methods. The relative accuracy and precision of the wind data have been validated using a five-beam profiler to measure simultaneous independent profiles (Strauch et al. 1987); the effects of precipitation are discussed by Wuertz et al. (1988). Numerous comparisons of winds measured by profilers and radiosondes (Larsen 1983) show results that are similar to radiosonde-radiosonde comparisons (on the order of 1 m s^{-1}). When there are no interfering signals, the time-height wind profiles are usually very impressive.

2.4. **Limitations.** A decade of experience with a variety of UHF Doppler wind profilers is available for judging their performance. A major limitation is the assumption of local horizontal uniformity, mentioned in section 2.2. If this condition is met and the return signal is strong enough, then only one cycle of the antenna beam pointing positions is needed to measure the wind. However, time-height profiles of wind data show that local horizontal uniformity is rarely, if ever, satisfied. What has been demonstrated by comparisons with radiosondes is that the profiler can measure mean wind profiles when the radial velocities are averaged over a number of cycles of antenna pointing positions. The averaged radial velocities are then representative of the actual mean radial winds, at least in most meteorological conditions. If the mean wind is not horizontally uniform during the averaging time, then the averaged radial velocities may not be representative. Meteorological conditions in which short spatial and temporal scales of variability have amplitudes as large as the mean, such as the CBL and severe storms, limit the use of profilers for measuring horizontal wind profiles. Note, however, that even in these cases the radial velocities measured by the profiler may be very accurate even for just one antenna cycle, and, as long as these radial velocity profiles are treated independently, the data can portray the dynamics of the radial velocity field if the sampling interval is sufficiently short.

Another condition that can cause the local horizontal wind uniformity assumption to be invalid, even with temporal averaging, is the presence of gravity waves. The vertical velocity measured by the zenith beam can be very different from the vertical velocity at the oblique resolution volumes, and if, for example, the waves are standing waves, temporal averaging will not reduce the difference. The gravity waves of most concern are those with spatial scales less than the resolution volume separation and temporal scales longer than the profiler averaging time. The extent of problems caused by gravity waves in profiler data is not known; however, gravity waves with amplitudes large enough to cause errors are not uncommon (VanZandt 1982, 1985; Nastrom and Gage 1984; Nastrom et al. 1990; see also section 4.2).

Profiler data can have problems caused by interfering signals, even with well-designed and properly operating systems at relatively clutter-free sites. The primary sources of interfering signals are

- ground and sea clutter,
- radio frequency interference (RFI),
- migrating songbirds, and
- atmospheric echoes in radar sidelobes.

Not included in this list are transitory targets that may have very strong echoes, such as aircraft or birds, but whose transitory nature allows conventional profiler data processing to operate satisfactorily.

When the desired atmospheric echo is separated in velocity and stronger than the interfering signal, conventional processing is able to extract valid mean velocity estimates. A number of techniques have been developed and tested to extract valid mean velocity estimates when the atmospheric echo is separated in velocity but weaker than the interfering signal. The most difficult problem arises when the atmospheric echo and the interfering signal have nearly the same mean velocity. This problem is most prevalent in the lower altitude gates (especially on the vertical beam) where ground clutter echoes are present. With present data processing, the clear-air vertical velocities measured in the lowest few kilometers by the vertical beam of UHF Doppler profilers are biased and generally useless if there is ground clutter. Jordan et al. (1997) and May and Strauch (1998) describe methods for reducing the clutter power without affecting the desired signal even when the velocities are not separated; however, these methods have not been implemented in currently available processing. The inability of UHF profilers to measure vertical winds at low altitudes because of ground clutter is particularly frustrating because the upper-level vertical winds are found with such accuracy that they promise unique data for numerical models. Sea clutter is another example of interference that has a distinctive spectral signature that can be used to identify and remove it. Again, no techniques have been implemented in commercial profilers to do this, and atmospheric spectra can overlay the sea clutter spectra, resulting in a bias in the wind velocity estimates.

RFI has not been a major issue in the past, but it is likely to become one soon as UHF systems move from 404 MHz to 449 MHz, the recently approved operational profiler frequency. The 449-MHz profilers will see amateur radio repeaters. Other UHF profiler frequencies will be under increasing pressure from all kinds of communication systems. In some cases it is possible to choose operating parameters for the profiler that will mitigate the effects of RFI, which tends to be spread only a few kilohertz.

Problems caused by migrating birds have received considerable attention in the past few years (e.g., Wilczak et al. 1995). Automated ways to recognize bird contamination in the wind data have been developed. For example, Merritt (1995) describes a method that allows the winds to be measured in the presence of bird or other contamination as long as the contamination is intermittent.

Strong signals in antenna sidelobes can be generated by thunderstorms, but can also occur if there is a very strong horizontally stratified reflectivity layer. Layer reflectivity in a sidelobe usually appears at higher altitude resolution volumes where the reflectivity is low. This type of interference has not been identified as a major concern in UHF profilers.

Much of the interference (except bird echoes) would be eliminated if profiler antennas had better sidelobe performance. Given that the minimum detectable signal for wind measurement is of the order of -150 dBm and the transmitted power is of the order of +60 dBm, it is unlikely that the antenna can be improved enough to eliminate interference. Thus, improved data processing methods are needed.

2.5. **Performance.** The performance of any wind profiler is limited by its sensitivity, which improves with higher transmitted power levels and larger antennae. The returned signal strength is also a function of the refractive index structure parameter (C_n^2), which tends to decrease with height and is dependent on meteorological conditions. Thus if C_n^2 is small, returned power may not be strong enough to make a meaningful measurement of the wind. An important indicator, then, is the percentage of time wind measurements are reported. Figure 2-2 shows the percentage as a function of height for a network of 29 wind profilers from June 1992 through May 1994 (Barth et al. 1994b).

Numerous studies have compared wind-profiler-measured winds with winds measured by other types of instruments (Balsley and Farley 1976; Farley et al. 1979; Fukao et al. 1982; Larsen 1983; Lawrence et al. 1986). Weber and Wuertz (1990) made an extensive comparison of wind measured with a UHF wind profiler and rawinsondes over a 2-year period at Stapleton Airport in Denver, Colorado. Differences with a standard deviation of 2.5 m s^{-1} were attributed mainly to natural variability in the wind fields. Strauch et al. (1987) used a five-beam UHF profiler to derive independent near-simultaneous three-beam measurements of the horizontal wind during February 1986. They found a standard deviation of 1.3 m s^{-1} for these clear-air observations. Wuertz et al. (1988) repeated the experiment between May and August, when rain could be expected. When rain drop fall speeds were properly included in the horizontal wind calculations, errors of 2–4 m s^{-1} were found.

2.6. **Future Enhancements**. Continued integration of wind profiling technology into operations and research requires continued improvement in the reliability and accuracy in the derived meteorological products. In particular, extracting measurements of meteorological quantities in the presence of interfering signals and quantifying the error in the measurements introduced by nonhomogeneous and other limiting meteorological conditions must be addressed. Certainly, improvements in profiler hardware offer some advantages and must be pursued; however, these improvements will be incremental. Significant improvements are possible through signal processing advances discussed in this section. Ideal antennas would eliminate all the interfering signals listed in section 2.4 except for migrating birds. However, the sensitivity of the profiler receiving system is such that a significant improvement in antenna sidelobe performance may not dramatically reduce the interference problem. Nevertheless, improving antenna sidelobe performance would help and should be the priority for hardware developers.

Other hardware (i.e., better solid-state transmitters, digital receivers, and automated reflectivity calibrations) would improve profiler performance, especially reliability. The problem of saturation in precipitation could be addressed if the dynamic range of the typical linear receiver used in UHF Doppler profilers were large enough to allow reflectivity measurements in heavy precipitation. This could be done with some combination of more dynamic range in the analog-to-digital converters (ADC), a separate logarithmic reflectivity channel, dual linear channels, and dynamic automatic gain control (AGC).

Current signal processing methods generally follow the techniques described in section 2.2 and by Barth et al. (1994a). A limiting assumption in the current algorithms is that the atmospheric return is the only signal present. Contamination can obscure, or be mistaken for, clear-air return from the atmosphere, resulting in erroneous or even meaningless measurements. While the consensus average technique eliminates much contamination, it is sometimes ineffective, and it may restrict temporal resolution. Methods such as postprocessing and quality control are not always effective because important information may be lost during the early stages of signal processing. In some cases, postprocessing may not detect contamination without other independent measurements.

Improvements in the timeliness and quality of wind profiler products will depend on improving the signal processing. Figure 2-3 shows the steps involved in a more robust profiler signal processing system now under development (Merritt et al. 1997; Wilfong et al. 1997). Signal processing begins with time series acquisition. If potential interference of a known frequency is present, e.g., amateur radio operations, the interpulse period can be chosen so that interference does not fall at a harmonic of the sampling frequency. Low-pass filtering and compression may be done in either the time or the frequency domain, or both. Producing a highly resolved spectrum requires very long, uninterrupted time series. In addition to allowing the traditional boxcar average, one may use a more optimally weighted filter or no filter at all. A long, optimized digital Fourier transform (DFT) may be used to compute the spectrum, and radial velocities larger than, say, 10 to 40 m s^{-1} are discarded. A long DFT does not compromise the benefits of time-domain averaging because both are coherent processes. Thus, in addition to data compression, spectral clipping accomplishes bandpass filtering in the spectral domain.

Traditionally, numerous spectra collected over a minute or so have been simply averaged incoherently to reduce variability, and thereby increase signal detectability. When some of the spectra are contaminated (e.g., by RFI, bird echoes), a simple average can produce a contaminated mean spectrum in which the atmospheric signal is obscured. Intermittent contamination is reduced or eliminated using other smoothing techniques such as a statistical averaging method (Merritt 1995).

Profiler spectra often contain multiple signals, *none* of which may be due to radar return from the atmosphere. The next-generation signal processing should accommodate signal detection and identification algorithms and techniques that (1) determine the presence of multiple signals in each spectrum, (2) model data to estimate spectral moments of noise and signals, and (3) use quality controls to identify signals associated with radar return from the atmosphere. Elimination of nonatmospheric signals is the most difficult and error-prone part of signal processing. Consistency over time and over space is the most general principle affecting confidence in signal identification and can be used to identify and reject nonatmospheric signals. Further, if a five-beam configuration is used, opposing beam signal consistency can be checked.

Most of the meteorological products desired from wind profilers require the combination of independent measurements made on antenna beams pointed in different directions. To compensate for temporal and vertical sampling differences, the data from the different beams are interpolated to a common time-height grid prior to being combined to form final wind profiler products. In addition to the accumulated confidence estimates associated with signals prior to gridding, new confidence values are introduced describing the fit of the data to the common grid. It is not possible to compensate for the horizontal spatial separation of the measurements. With profilers using more than three beams, additional confidence estimates can be derived that indicate the degree of horizontal homogeneity present. Such confidence estimates are an essential part of the final products from wind profilers.

New processing methods (Merritt et al. 1997; Wilfong et al. 1997) are being tested on a variety of data. For example, moment data gathered during the 1997 Southern California Ozone Study (SCOS97) have been processed using both conventional and new processing techniques that employ spatial and temporal continuity. The dramatically increased coverage (see Fig. 2-4) shows the value of the new processing method.

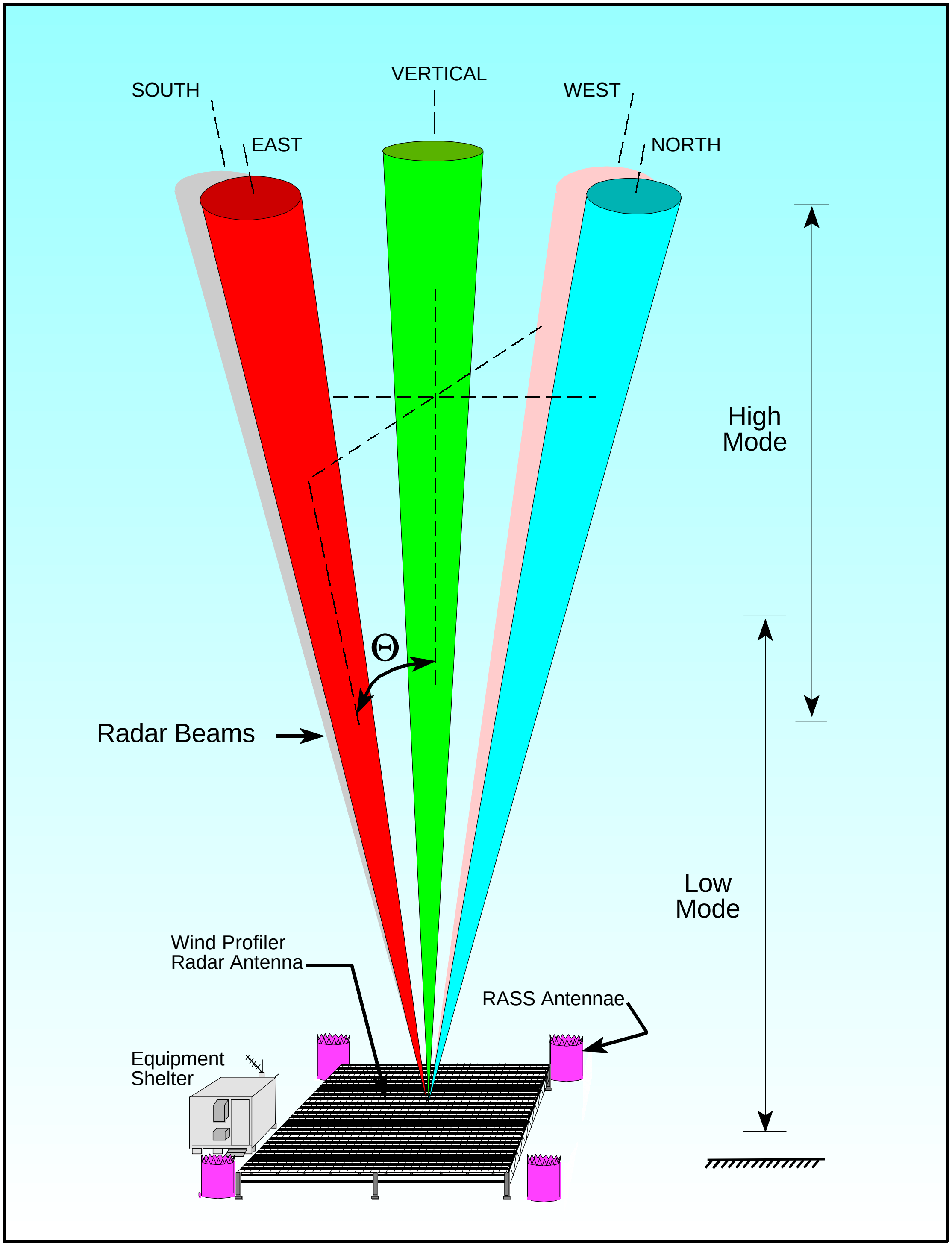

Figure 2-1. Typical wind profiler beam configuration consisting of three to five beams: one vertical, and two or four tilted near 15 degrees from the zenith in orthogonal directions. Many profilers employ overlapping low and high modes where power and height resolution may change. The acoustic source for RASS are typically located around the radar antenna, as shown.

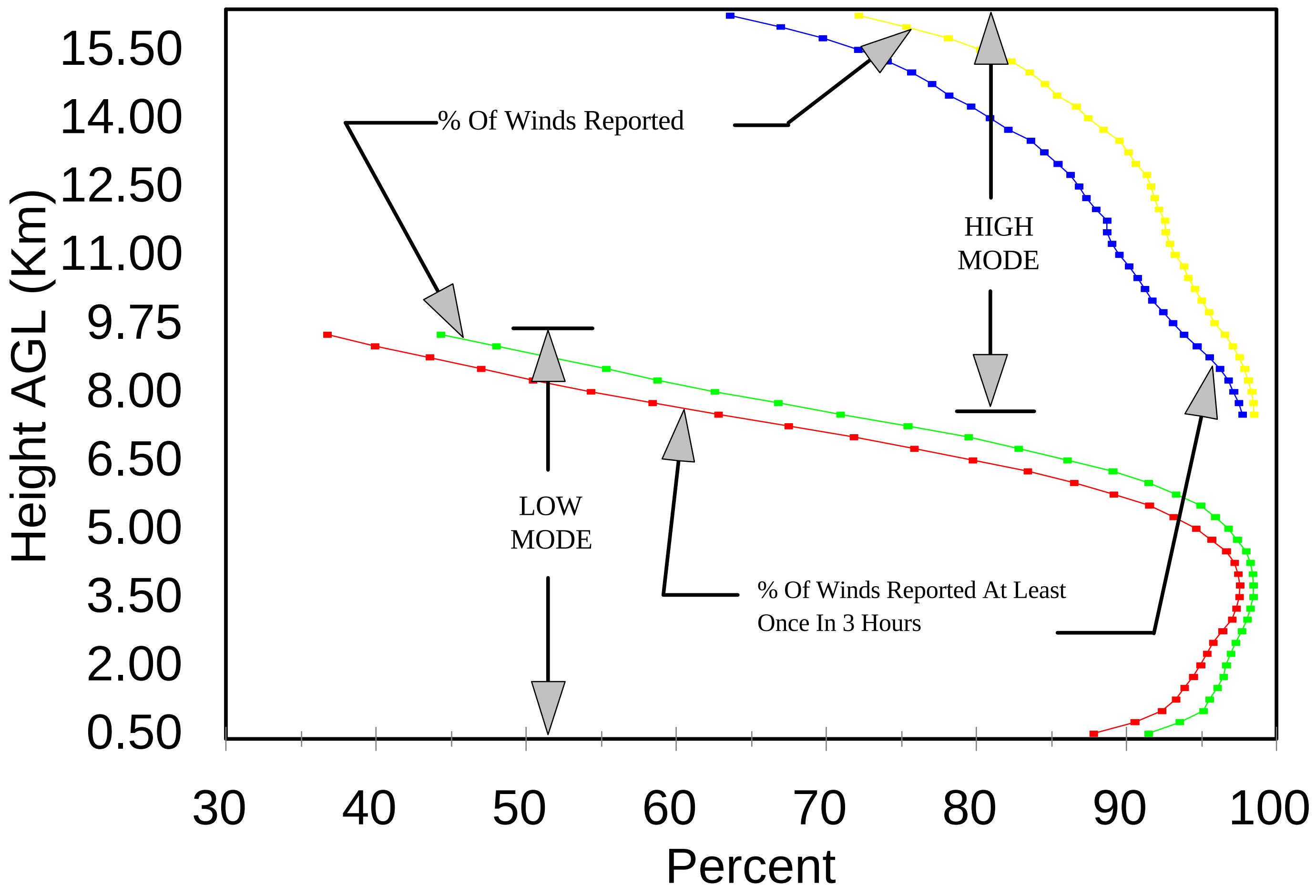

Figure 2-2. Percentage of time hourly winds were derived and passed quality control, as a function of height. Data were averaged over 29 of the national network profilers from June 1992 through May 1994. The top pair of curves is for the high mode, and the bottom pair is for the low mode (see Fig. 2-1).

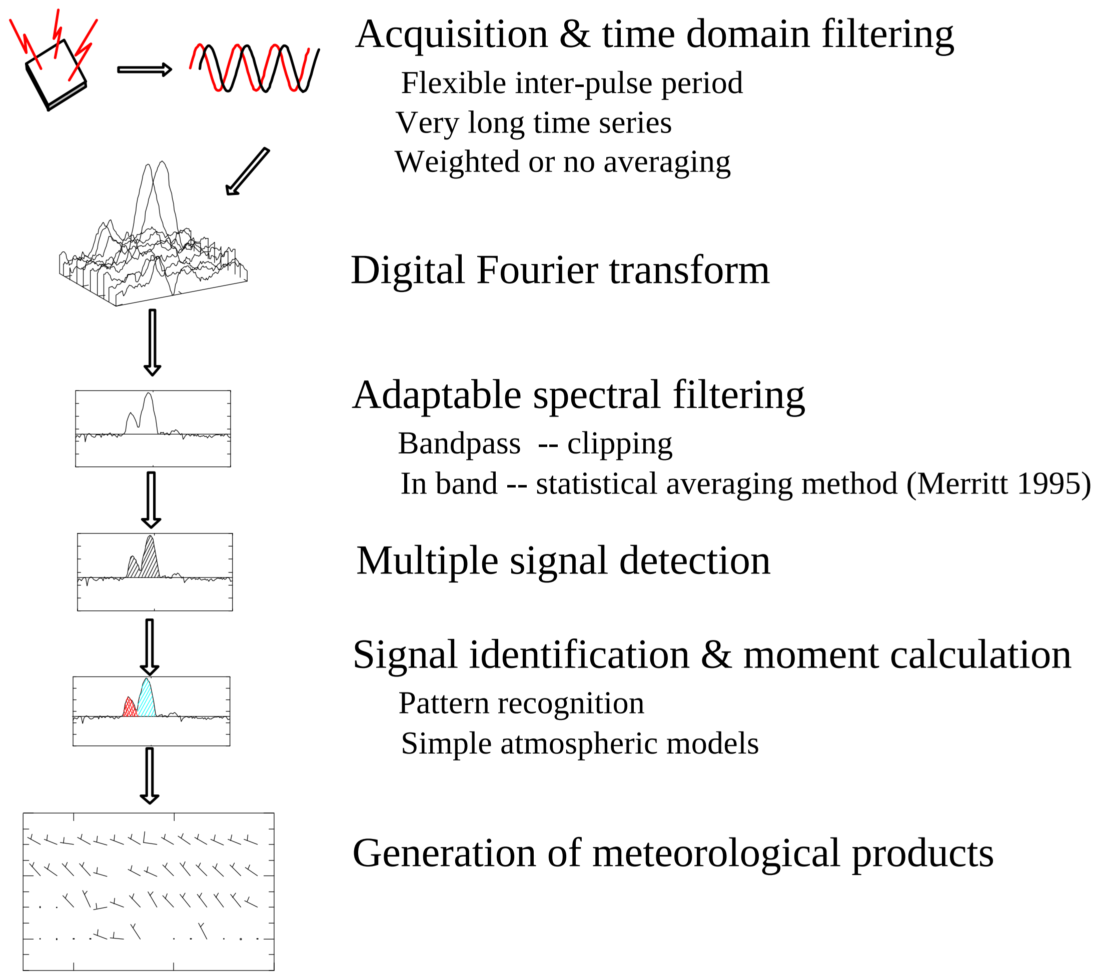

Figure 2-3. Signal processing steps being developed for the next-generation wind profilers.

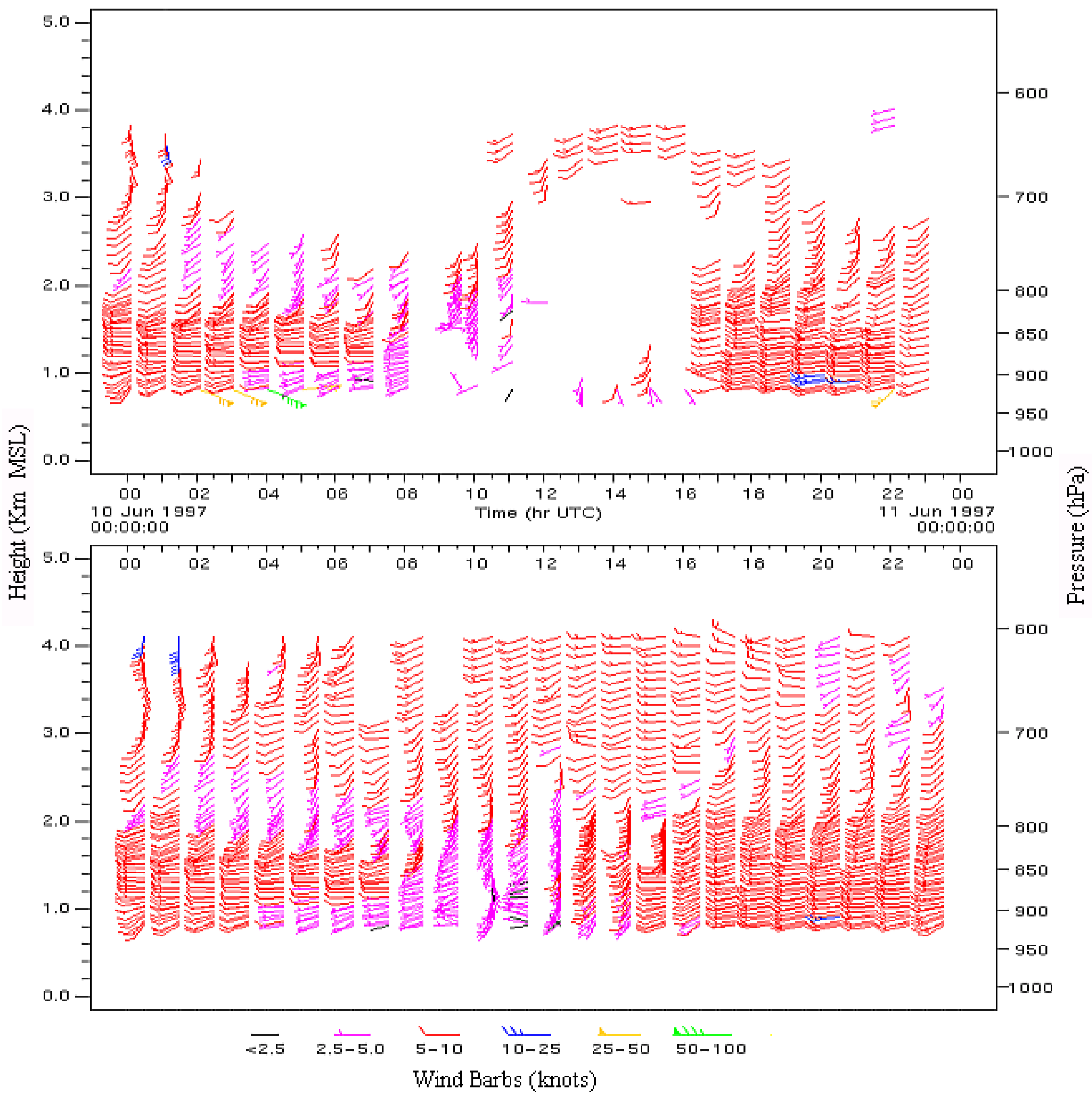

Figure 2-4. Top: Conventionally processed wind profiler data from a 915-MHz boundary layer profiler located at Barstow, California, for the period 0000 UTC 23 July 1997 to 0000 UTC 24 July 1997. Wind profiles were produced by treating the moments from each beam (i.e., the signal power, radial velocity, and spectral width) with a conventional consensus average technique. Bottom: The same moment data, but treated with an analysis using temporal and spatial continuity (Wilfong et al. 1997).